Current Transformer Active Interlock Summary for Concurrent BLIP/RHIC Operations
M. Wilinski
5-5-05

Background:

The Brookhaven 200 MeV linac is a multipurpose machine used to inject low intensity polarized protons into the Booster that ultimately end up in RHIC as well as to inject high intensity protons to a medical isotope production facility (BLIP). The BLIP facility is directly off the linac. A potential problem might arise when the linac is used to fill RHIC with polarized protons. Equipment and sensitive electronics at RHIC might be damaged and administrative radiation limits exceeded if high intensity protons are injected by mistake, therefore, the high intensity source is valved off at the upstream end of the linac during RHIC fills. During BLIP operation, several large bending magnets are interlocked off, preventing the high intensity protons from reaching RHIC. This changeover from polarized to high intensity protons takes a fair amount of time and is usually done only when operations is confident that another RHIC fill will not be needed soon. This interlocking procedure has a serious adverse impact on the BLIP program. The RHIC polarized proton and BLIP high intensity proton programs have only rarely run simultaneously.

To allow concurrent RHIC & BLIP operation, a dedicated pair of transformers were installed in the AGS ring. The redundant transformers are placed in the B15 section of the AGS ring and the electronics are located in the B18 House. The transformers were placed in AGS as opposed to somewhere upstream, namely in the linac, because the utilization of pulsed transformers at the end of the linac or booster would require more sophisticated electronics and timing considerations. Placing two DC transformers for an interlock in the AGS ring would be the last line of defense (a whole array of other protections would have to break down) if high intensity protons for BLIP would somehow end up in the AGS with the magnets to RHIC on. The operation of the transformers themselves are verified with "keep alive" circuits. The end result of too much beam in the AGS ring - for whatever reason - would be that the bending magnets to RHIC would be interlocked off, the beam would be driven into the dump, and AGS beam shutdown.

Transformers:

New Parametric Current Transformers (NPCT) from Bergoz are used for monitoring the beam in the AGS ring. This transformer is a DC current transformer with a 20A full scale input, 175mm inner diameter, and improved radiation resistance. Bergoz has implemented a “keep-alive” circuit by presenting a constant current with amplitude 15mA RMS at a frequency of 31.25kHz into the system. Bergoz’s website is: http://www.bergoz.com.

The NPCT has undergone a major engineering overhaul in efforts to improve on the original design of the PCT. The new PCT now has four full-scale ranges controlled by TTL bits: +/-20A, +/-2A, +/-200mA, and +/-20mA. The –3dB output bandwidth is 10kHz and the resolution in a one second integration period is 5uA RMS (i.e. 1E7 dynamic range, 24 bits, in range +/-20A). Bergoz has also streamlined the PCT electronics package by combining the front-end and back-end packages into one 3U chassis. This allows the use of one cable per transformer instead of the previous configuration of two cables per transformer. The cable Bergoz selected for use is Belden 9508NH (non-halogen) that consists of 8 wire pairs with an outer diameter of just over 8mm. The rad-hard PCT has a 3-meter 9508NH cable off the sensor head terminated by a DB15 connector. A filter box, containing passive components only, is placed at the end of the sensor cable. Another interconnecting 9508NH cable is then used between the filter box and the electronics

chassis. The new PCT has also been modified to remove effects of fill-pattern dependence on the sensor readout.

PCT Transformer Usage at BNL & Other Facilities

Julien Bergoz has conveyed some information regarding usage of PCTs at other laboratories:

- The storage ring at ESRF (European Synchrotron Radiation Facility, Grenoble, France) has 3 PCTs and compares their outputs permanently. It is possible other machines do the same, but Bergoz is not aware of such.
- CERN had an administrative authorization to run LEP up to 100 GeV/beam and a given number of mA. The PCTs were monitored so that the maximum allowed stored current was not exceeded.

Four PCTs have been installed at BNL in years past and are currently operating in the Booster, AGS, and RHIC rings. These transformers are used for intensity monitoring and after passing through a series of electronics, eventually display the number of ions circulating in the given ring in the main control room (MCR). Others have access to the results by use of "comfort displays" on televisions located around the site.

PCT Transformer Failure Analysis

A rough MTBF from Bergoz is as follows: First, assume that all PCT/MPCT (modular parametric current transformer) units are operating permanently except during machine shutdowns, say 6000 hours/year. The first units shipped 18 years ago are still operating. Interventions on the PCT/MPCT electronics have mostly been motivated by the electronics being upset by the revolution frequency. Hard failures are very few. Bergoz can remember only 3 out of more than 300. Those 300 have an average age of ca. 8 years. A rough MTBF calculation based on actual data comes to >47000 hours. Calculated MTBF (projection) would indicate a much longer time.

Bergoz also performed a draft failure analysis on the PCT dated March 14, 2004 (see BNL.failure.analysis.pdf) in which he states various failure conditions and some good practices to avoid failures.

Interlock Electronics

The current transformer electronics process the current and convert it to a voltage equivalent analog signal based on the range setting of the electronics. The interlock module takes as its input the current transformer analog signal for processing. The input is split in three ways: (i) to a buffer for an output copy of the input, (ii) to a bandpass filter, and (iii) to a comparator circuit. The bandpass filter extracts the 31.25kHz keep-alive current and then sends it to a window comparator to look for the ~65mV RMS amplitude. The comparator circuit checks that the current transformer has measured a beam current below 140mA. If the keep-alive current is measured successfully and if the measured beam current is below 140mA, logic circuitry will send a high signal to the beam inhibit system and a contact closure to the security system indicating that both "system OK" conditions have been satisfied and beam can be extracted from the AGS. If the keep-alive current is not present in the system or if the measured beam current is above 140mA, the logic circuitry in the module will send a low signal to the beam inhibit system and a contact open to the security system indicating that a "system failure" has occurred and beam should not be extracted from the AGS.

Texas Instruments (TI) provides failure analysis on their individual ICs. On the interlock module, TI parts make up 9 out of 11 ICs. Table 1 is a summary of the failure data on the TI parts used.

Part #	MTBF	FIT	Temperature	Confidence	Activation Energy
BUF634U	$3.273 * 10^6$	9	125C	90%	0.7EV
LM339AD	$7.884 * 10^8$	1.27	55C	60%	0.7EV
SN74ACT244DW	$4.626 * 10^8$	2.16	55C	60%	0.7EV
SN74LS00D	$7.884 * 10^8$	1.27	55C	60%	0.7EV
SN74LS04D	$7.884 * 10^8$	1.27	55C	60%	0.7EV
SN74LS08D	$7.884 * 10^8$	1.27	55C	60%	0.7EV
SN74LS86AD	$7.884 * 10^8$	1.27	55C	60%	0.7EV
SN75189D	$7.884 * 10^8$	1.27	55C	60%	0.7EV
ULN2003AD	$7.884 * 10^8$	1.27	55C	60%	0.7EV

The failure rates are summarized by technology and mapped to the associated material part numbers. The failure rates are highly dependent on the number of units tested, therefore, it is not recommended to compare failure rates.

Definition of Table Terminology

MTBF: Mean Time Between Failures.
FIT: Failures-in-Time. The number of failures per 10E9 device-hours.
Temperature: Estimated usage temperature.
Confidence: Statistical confidence level.
Activation Energy: Energy in electron volts (eV) for a particular process to occur.

Table 1 – Texas Instruments IC Failure Analysis

The current limit can be tested by injecting a current above 140mA through the calibration winding of the transformer. A Keithley current source is interfaced to the calibration loops of each transformer to perform this test.

A secondary "warning" module has been designed to monitor the difference in measured currents between the two transformers. This will assist in determining if both transformers are set up for the same gain and if they have the same offset. The module takes both transformers' analog signals as inputs, subtracts them, and sends the difference signal through a window comparator with a marginal +/- voltage window centered around zero volts. This module is not expected to interlock any devices, but simply provide a warning through PET, or in some other manner, that the difference is not close to zero. It is expected that the two transformers should have similar responses and this module will monitor that similarity. Interlock capabilities have been included in this module in case it is required in the future.

Summary

The function of the new BLIP/RHIC current transformers is:

1) To monitor the circulating beam in AGS, and
2) To be used as an active interlock and prohibit AGS extraction when the circulating beam in AGS exceeds 140mA.

The interlock process is as follows:

1) The current transformers read the circulating beam current of the AGS from the time of beam injection to beam extraction. Note that extraction will only take place if the current remains at an acceptable value (below 140mA).
2) Interlock electronics modules monitor the output of the PCT electronics. Fault conditions occur when the measured current exceeds 140mA or when the electronics detect that the keep-alive current is not measured at 31.25kHz, 65mV RMS.
3) The outputs of the interlock modules are used as an input to the beam inhibit system and security system to inhibit AGS extraction when a fault is sensed. Two different failure modes are possible for each transformer – an over current limit fault and a keep-alive monitor fault.
4) A test system with a current source is used as part of a formal procedure to test for normal operation of the transformer and its interlocks. If the operation of the current transformer is found to be abnormal, concurrent operation of BLIP & RHIC will not be allowed until further investigation and repair resolves the problem.